Final: 1 Oct 92 to 30 Sep 93

The Application of Smooth Pursuit Eye Movement Analysis To Clinical Medicine

PE: 61101F
PR: ILIR
TA: AC
WU: 34

Edward J. Engelken
Kennith W. Stevens
Ann F. Bell

Armstrong Laboratory (AFMC)
Aerospace Medicine Directorate
Clinical Sciences Division
Brooks AFB, TX 78235-5117

AL/AO-JA-1993-0052

We analyzed pursuit racking eye movements from selected neurological patients and compared them to the responses of 20 normal subjects. The patients/subjects tracked a small spot of light moving sinusoidally in the horizontal plane at a frequency of 0.4 Hz and a peak-to-peak amplitude of 40 . The eye-movement responses were separated into a smooth-pursuit component and a saccadic component. We calculated the asymmetry as well as the gain and phase response of the smooth-pursuit component. The saccadic component was quantified by calculating the percentage of the total tracking movement contributed by the saccadic system. The patients with smooth-pursuit impairment exhibited a higher percentage of saccadic tracking and a lower smooth pursuit gain compared to the normal subjects. One patient with a unilateral lesion exhibited significant asymmetry in the smooth-pursuit component. In this case, the direction of the asymmetry indicated the side of the lesion.

Eye Movements, Smooth Pursuit Tracking, Ocular Tracking
Saccades

UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UL

The Application of Smooth Pursuit Eye Movement Analysis to Clinical Medicine

EDWARD J. ENGELKEN, M.S., Ph.D., KENNITH W. STEVENS, B.S., and ANN F. BELL, B.S., M.D.

ENGELKEN EJ, STEVENS KW, BELL AF. *The application of smooth pursuit eye movement analysis to clinical medicine.* Aviat. Space Environ. Med. 1994; 65(5, Suppl.):A62–65.

Pursuit tracking eye movements were analyzed from selected patients with neurological injuries and compared to the responses of 20 normal subjects. The patients/subjects tracked a small spot of light moving sinusoidally in the horizontal plane at a frequency of 0.4 Hz and a peak-to-peak amplitude of 40°. Eye-movement responses were separated into a smooth-pursuit component and a saccadic component. The smooth-pursuit component was analyzed by calculating the gain, phase, and asymmetry. The saccadic component was quantified by calculating the percentage of the total tracking movement contributed by the saccadic system. The patients with smooth-pursuit impairment exhibited a higher percentage of saccadic tracking and a lower smooth pursuit gain compared to the normal subjects. One patient with a unilateral lesion exhibited significant asymmetry in the smooth-pursuit component. In this case, the direction of the asymmetry indicated the side of the lesion.

THE SMOOTH PURSUIT (SP) eye-movement system operates in concert with the saccadic system to allow visual acquisition and tracking of moving targets (Fig. 1). Saccades are rapid eye movements of refixation that enable one to quickly place the image of a target on the fovea. SP movements are generated to maintain the image on the fovea as the target moves. Saccades are high velocity (up to 800°/s), short duration (20–120 ms) eye movements during which vision is suppressed. SP movements have a maximum velocity of about 50 to 80°/s, but visual acuity is maintained during SP. Normally, tracking a target moving smoothly at a modest velocity generates predominately SP eye movements interspersed with a few "catch-up" saccades. If the SP system becomes impaired, the saccadic system is called into action more often as the SP system fails to keep pace with the target motion. Complete failure of the SP system results in "staircase tracking" consisting of a continuous sequence of pure saccadic eye movements.

A number of clinical tests of the SP system have been reported over the last 20–25 years (1–3,10–12). The early tests consisted of having patients track a swinging pendulum and recording eye movements using standard electrooculography (EOG). The recordings were analyzed by visual inspection. Increased saccadic tracking was taken as an indicator SP dysfunction, and unilateral lesions were often found to cause impaired SP tracking toward the side of the lesion (2,3). Later, computer driven displays and computer analysis of the recordings were developed. We began to explore computerized SP testing at the Armstrong Laboratory in the late 1970's (4,13). In 1989 we replaced our EOG eye-movement recording system with an infrared reflectance system, and upgraded our data analysis procedures (7). Since that time we have developed new, more powerful methods to analyze eye movements using nonlinear adaptive digital filters (8,9). These new analysis methods, originally developed for the analysis of nystagmus, have enabled us to implement a new, more sensitive test of the SP eye-movement system. We are now able to accurately separate the eye-movement responses into an SP component and a saccadic component and analyze each component separately.

METHODS

Subjects

We tested 20 normal subjects ranging in age from 21 to 38; median age was 29. There were 13 men and 7 women. Subjects were all active duty military personnel with no history of disease or injury that might affect tracking performance. All subjects were briefed as to the purpose of the research and the testing procedures to be used. The voluntary, fully informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169–6. In addition to the normal subjects, a number of selected patients with neurological problems were tested to assess the effect of known lesions on SP tracking.

From the Armstrong Laboratory, Aerospace Medicine Directorate, Clinical Sciences Division, Brooks AFB, TX.

Address reprint requests to: Dr. Edward J. Engelken, who is Chief of the Vestibular Laboratory, Armstrong Laboratory (AFMC), Aerospace Medical Directorate, Clinical Sciences Division, 2507 Kennedy Circle, Brooks AFB, TX 78235-5117.

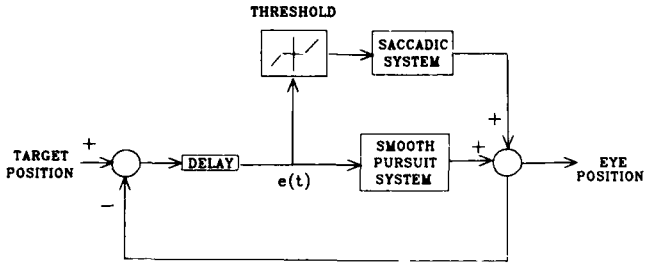

Fig. 1. Simplified block diagram of the pursuit tracking system. Differences between the target and eye position signals produce a delayed error signal, e(t). If e(t) exceeds a certain threshold, the saccadic system is activated causing a refixation eye movement to reduce the error to near zero. As the target moves, the SP system will act to match the eye velocity to the target velocity. If the target motion is smooth and the SP system is successful in keeping e(t) small, few saccades will be produced. Failure of the SP system to keep e(t) small results in more frequent activation of the saccadic system. In this simplified model, the combined tracking response (eye position signal) is the sum of the saccadic system and SP system outputs.

Apparatus

Subjects/patients were instructed to track a small spot (628 nm) of red light moving sinusoidally in the horizontal plane while the movements of both eyes were recorded. The target was generated by a 1-mW, He-Ne laser. A General Scanning G-300DP scanner and a General Scanning CCX-650 controller provided the target motion. The target was projected onto a curved screen located 2 m in front of the subject. Target motion was sinusoidal, with a peak-to-peak amplitude of 40° and a frequency of 0.4 Hz. Peak target velocity was 50.3°/s. The subject's head was stabilized by means of a bite bar. Eye movements were recorded using a modified version of the infrared reflectance device previously described by Engelken et al. (6). A Compaq DeskPro 386/33 computer equipped with an Analog Devices RTI-802-8 digital-to-analog converter board and an RTI-800-A analog-to-digital converter board were used to generate driving signals for the scanner and digitize the eye-movement responses. The eye-movement signals were digitized to a resolution of 12 bits at a rate of 125 Hz. The eye-movement signals and the target position were stored in files on the hard disk for later analysis.

Data Analysis

Subjects tracked a total of 10 cycles of target motion, but only the last 8 cycles were digitized. The first 2 cycles were discarded to eliminate start-up transients and to obtain a representative segment of steady-state tracking. Tracking periods contaminated with eye blinks were discarded. The digitized eye-position signal (Fig. 2, trace 2) was passed through a band-limited (40 Hz) differentiating digital filter (5) to produce an eye velocity signal (trace 3). The eye velocity was then processed by an adaptive asymmetrically trimmed-mean digital filter (8,9) to extract the SP component of the eye-velocity signal (trace 4). Subtracting the SP component from the original eye-velocity signal produced the saccadic velocity component (trace 5). The SP velocity and saccadic velocity components were integrated to yield the SP position signal (trace 6) and the saccadic position signal (trace 7).

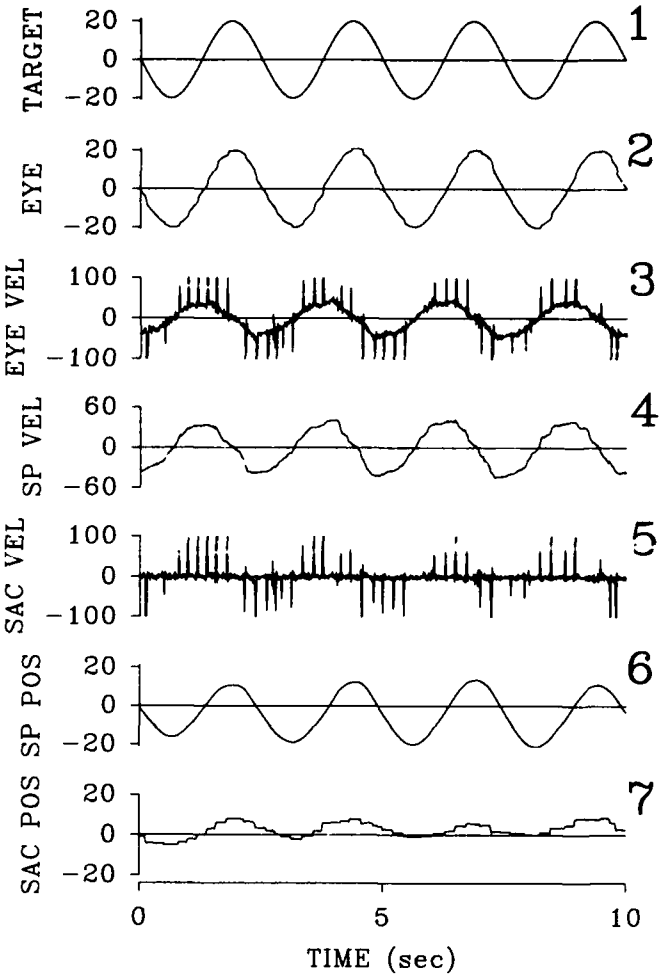

Fig. 2. Eye-movement signal processing. A subject tracks the target (trace 1) as the resulting eye movements are recorded. The eye-movement signal (trace 2) is broken down into component parts in a series of steps (traces 3–7) as described in the text. Position signals are given in degrees; velocity signals are presented in degrees/second. Upward deflections represent movements to the right. Only 4 cycles of the tracking record are shown.

The combined tracking performance includes contributions by both the SP and saccadic systems. We quantified combined tracking by calculating the gain and phase response using the target signal as the system input and the eye position signal as the system output. In order to quantify the relative contributions of the SP and saccadic systems to the combined performance, we calculated a parameter called Percent Saccadic Tracking (PST). PST was defined as:

$$PST = \frac{\int_0^{20} |\,SAC\ VEL\,|\,dt}{\int_0^{20} |\,EYE\ VEL\,|\,dt} \times 100\%$$

where SAC VEL is the saccadic velocity signal (Fig. 2, trace 5) and EYE VEL is the eye-velocity signal (Fig. 2, trace 3). The integrations were carried out over the 8 cycles (20 s) of tracking. PST represents the percentage of the tracking eye movements contributed by the saccadic system. A PST of 10 indicates that 10% of the combined tracking response is due to saccadic tracking.

The SP tracking component was analyzed separately. SP was quantified by calculating the gain and phase response of the SP component using target velocity as the input and SP velocity as the output. In addition, we calculated the asymmetry of the SP component. Smooth Pursuit Asymmetry (SPA) was defined as:

$$SPA = \frac{\int_0^{20} SP\ VEL\ dt}{\int_0^{20} |\ SP\ VEL\ |\ dt} \times 100\%$$

where SP VEL is the SP eye-velocity signal (Fig. 2, trace 4). These parameters were computed for all 20 subjects and statistically analyzed to determine the mean values and the 95% confidence limits for future measurements. We also tested the parameters for right-eye, left-eye differences.

RESULTS

The results of the statistical analysis of our normal data are summarized in Tables I and II. Table I presents the analysis of the combined tracking performance; Table II, the analysis for the SP component. No significant differences between right and left eye responses were found. The results presented in the Tables represent pooled responses from both eyes. The combined tracking response includes the contribution of the saccadic component and yields higher gain than the SP component, as expected.

CASE REPORTS

In addition to the 20 normal subjects, we also tested several patients with known or suspected neurological problems. The following case reports represent typical findings.

Case Report 1

A 23-year-old foreign pilot trainee suffered a minor head trauma in a motor vehicle accident. He received a head CT scan for the head trauma and an incidental, 6-cm left temporal subarachnoid cyst was discovered. He denied headaches, hearing loss, tinnitus, otalgia, vertigo, imbalance, and facial nerve dysfunction. Although his left anterior ventricle was mildly effaced, he suffered no hydrocephalic symptoms. Otolaryngologic and neurologic examinations were normal.

Complete audiogram and auditory brain stem responses (ABR) were normal. Electronystagmography and EquiTest™ dynamic platform posturography were normal. Smooth pursuit eye tracking (Fig. 3B) was normal with SP gain of 0.97 (normal 0.825 to 1.05) and a PST of 7 (normal 1 to 20).

Neurosurgical and neurology consultants recommended that surgical resection or shunting was not indicated at this time for a probable congenital, slowly enlarging subarachnoid cyst. He was not recommended for flight duties.

TABLE I. COMBINED TRACKING RESPONSE ANALYSIS—MEANS AND 95% CONFIDENCE LIMITS.

Parameter	Lower 95%	Mean	Upper 95%
Total Gain	0.963	1.037	1.11
Phase (deg)	−3.22	−0.922	1.38
PST (%)	1.01	9.29	19.77

TABLE II. SMOOTH PURSUIT COMPONENT ANALYSIS—MEANS AND 95% CONFIDENCE LIMITS.

Parameter	Lower 95%	Mean	Upper 95%
SP Gain	0.825	0.938	1.05
Phase (deg)	−4.46	−1.54	1.38
SPA (%)	−7.05	0.06	7.17

Case Report 2

A 28-year-old active duty bomber pilot with a 3-year history of gradual left-sided hearing loss and tinnitus presented to his flight surgeon in 1989 with headaches that occurred when he jumped, sat down hard, or laughed. Otolaryngology examination was normal except for a left hearing loss. Head CT scan revealed a 5 × 6 cm left acoustic neuroma.

Surgical resection required two stages, approximately 6 months apart. After the first surgery he developed an *E. coli* meningitis that was treated with intravenous and intrathecal gentamicin. His facial nerve was stretched by the primary tumor and became dysfunctional after the first surgery. He later underwent a VII–XII nerve anastomosis with minimal improvement in facial motor function. He slowly regained his balance.

Examination at the Aeromedical Consultation Service 2 years after his last surgery demonstrated a total hearing loss on the left, House grade III of VI facial motor function (tone at rest, decreased motor function with synkinesis and 7-mm lid lag), a normal Romberg but an abnormal tandem Romberg.

Audiovestibular testing revealed normal right audiogram and ABR, with anacusis on the left. EquiTest™ dynamic platform posturography was abnormal in the sensory organization test conditions 5 and 6. Rotary chair testing of his vestibulo-ocular reflex revealed the expected low-frequency phase shift and decreased gain. His rotary chair response demonstrated normal symmetry, suggesting compensation for his unilateral vestibular loss. His SP tracking was severely impaired (Fig. 3C), especially when tracking to the left. SP gain was 0.45 (normal 0.825 to 1.05), PST was 57 (normal 1 to 20), and SPA was 53% (normal −7 to +7). He was not returned to flight duties.

DISCUSSION

Our analysis of pursuit tracking is based upon separating the tracking eye movements into SP and saccadic components. A normal subject (or patient with an intact SP system) should rely principally on SP eye movements to track the target used in our test. Low SP gain, increased PST and SPA are the chief indicators of pursuit tracking dysfunction. In Case Report 1, a patient is presented with a large subarachnoid cyst that did not compromise his SP tracking performance. The tracking test results complement the physical examination and the pathophysiologic characteristics of the lesion; i.e., a slowly enlarging nondestructive cyst.

The patient discussed in Case Report 2 presents

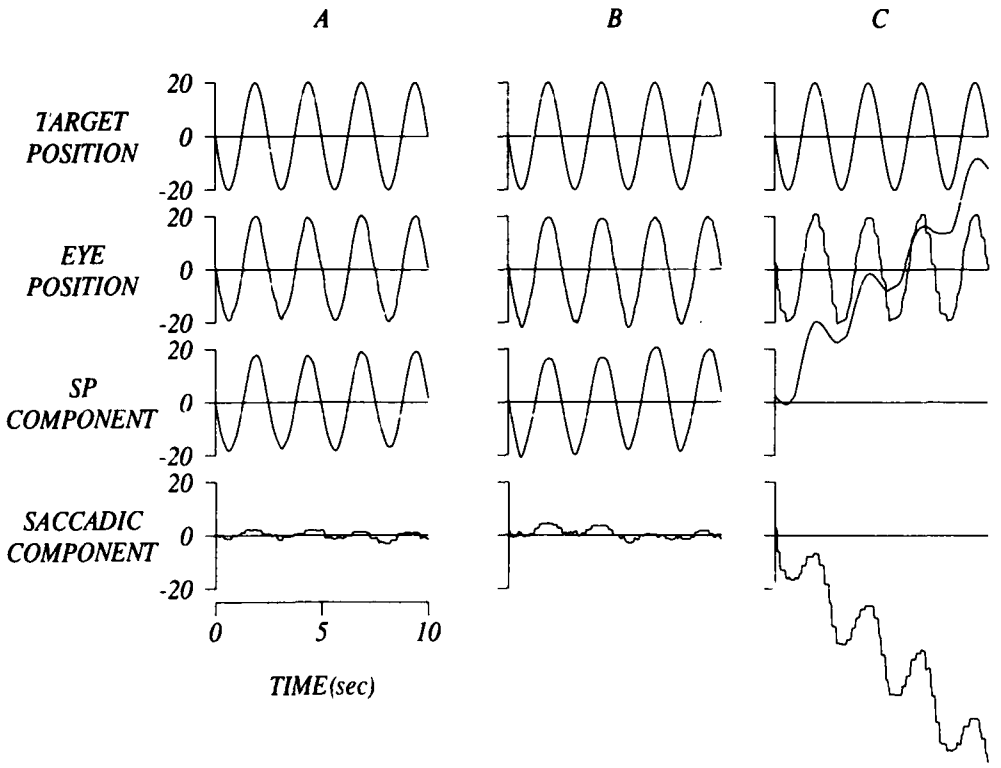

Fig. 3. Tracking record of a normal subject is shown in (A); tracking records for the patients discussed in Case Reports 1 and 2 are presented in (B) and (C), respectively. The eye position trace represents the combined tracking response and is the sum of the SP and saccadic components. Units of measurement are degrees of movement.

grossly abnormal tracking. This patient demonstrates how the saccadic tracking system "steps in" to compensate for a failed SP system. The combined tracking response (Fig. 3C, trace 2) is not as smooth as the normal subject response (Fig. 3A), but the patient is clearly following the target over its complete range of motion. Only when the combined response is broken down into SP and saccadic components is the extent of the dysfunction evident. The SP component (Fig. 3C, trace 3) deviates to the right (upward on the graph) indicating impaired SP tracking to the left, consistent with the patient's destructive left-sided lesion and extensive surgery. The saccadic component (trace 4) deviates to the left (downward on the graph) to compensate for the failure of the SP system. The combined tracking (trace 2) is the sum of the SP and saccadic components and demonstrates how well the compensation works. This patient's combined tracking gain is normal at 0.98. In this case, saccadic compensation makes up most of the deficit caused by an SP system operating with half the normal gain and considerable asymmetry.

The results presented in this paper are preliminary. We have not yet determined the relationship between increased saccadic tracking and visual acuity. We are currently developing a new tracking test in which structured targets will be used to assess dynamic visual acuity along with our current eye movement analysis.

ACKNOWLEDGMENTS

We wish to thank Mr. William G. Jackson for doing the statistical analysis for this study. We gratefully acknowledge the technical support provided by Sgt. Jerry Limburg and SrA. Moises Ramirez. This work was performed under project numbers 7755-27-15 and ILIRAC34. The research reported in this paper was conducted by personnel of the Armstrong Laboratory, Human Systems Center, AFMC, United States Air Force, Brooks AFB, TX. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Air Force.

REFERENCES

1. Baloh RW, Kumley WE, Sills AW, Honrubia V, Konrad HR. Quantitative measurement of smooth pursuit eye movements. Ann. Otolaryngol. 1976; 85:111–9.
2. Benitez JT, Bouchard KR. Electronystagmography: significant alterations in tumors of the cerebellopontine recess. Ann. Otol. 1974; 83:399–402.
3. Corvera J, Torres-Courtney G, Lopez-Rios C. The neurotological significance of alterations of pursuit eye tracking test. Ann. Otol. Rhino. Laryngol. 1973; 82:855–67.
4. Engelken EJ, Wolfe JW. A modeling approach to the assessment of smooth pursuit eye movements. Aviat. Space Environ. Med. 1979; 50:1102–7.
5. Engelken EJ, Stevens KW, Wolfe JW. Application of digital filters in the processing of eye movement data. Behav. Methods Inst. 1982; 14:314–9.
6. Engelken EJ, Stevens KW, Wolfe JW, Yates JT. A limbus sensing eye movement recorder. Brooks AFB, TX: USAF School of Aerospace Medicine, 1984; USAFSAM-TR-84-29.
7. Engelken EJ, Stevens KW, Enderle JD. Computer analysis of smooth pursuit eye movements. Biomed. Sci. Inst. 1989; 25: 127–33.
8. Engelken EJ, Stevens KW. A new approach to the analysis of nystagmus: an application for order statistic filters. Aviat. Space Environ. Med. 1990; 61:859–64.
9. Engelken EJ, Stevens KW, Enderle JD. Optimization of an adaptive nonlinear filter for the analysis of nystagmus. Biomed. Sci. Inst. 1991; 27:163–70.
10. Fletcher WA, Sharp JA. Smooth pursuit dysfunction in Alzheimers's disease. Neurology 1988; 38:272–7.
11. Hutton WA, Nagel JA, Loewenson RB. Variables affecting eye tracking performance. Electroencephal. Clin. Neurophysiol. 1983; 56:414–9.
12. Hutton WA, Nagel JA, Loewenson RB. Eye tracking dysfunction in Alzheimer-type dementia. Neurology 1984; 34:99–102.
13. Wolfe JW, Engelken EJ, Olson JE, Allen JP. Cross-power spectral density analysis of pursuit tracking: evaluation of central and peripheral pathology. Ann. Otol. Rhinol. Laryngol. 1978; 87:837–44.